SECTION IV: A Summary of the PA DEP Observations on the Effects of Undermining Interstate 79 during the 3rd Assessment Period

IV.A - Overview

The PA DEP requested an in-depth assessment of the effects of undermining Interstate 79 (I79) because of the high profile nature of the mining plan and an interest in gathering information that could be used to improve impact predictions. The PA DEP maintained a web page to keep the public informed about the status of mining beneath I79 and to the subsidence effects. Information collected by the PA DEP afforded an assessment of the duration and extent of land response to planned subsidence.

During the 3rd assessment period, I79 was undermined by portions of nine longwall panels. Three of the panels were extracted by the Emerald Mine and six by the Cumberland Mine, both in Greene County and both owned by Alpha Resources. Previous assessments of longwall mining under Pennsylvania's interstates had identified impacts to the highways but no danger to public safety was detected. In general, the magnitude and extent of impacts during the 3rd assessment period appeared to be similar as those identified in previous studies.

The most significant change in the character of the longwall panels, over previous assessment periods, was their greater size. In 2009, the average panel in the US had a width of 1,075-ft and a length of 10,995-ft (Fiscor, 2010). The nine longwall panels mined in the 3rd assessment period all exceeded previous averages and were among the widest in the US. They were supercritical in character with overburdens ranging between greater than 500-ft to less than 1,000-ft while undermining 3.4 miles of interstate highways.

IV.B - Data Sources

The PA DEP requested the University to summarize observations collected during the 3rd assessment period to evaluate and document the effects of undermining I79. Observations and photographs of impacts to the highway were made by PA DEP staff and entered into reports prepared by CDMO staff and statements written into the BUMIS database. In addition, PennDOT conducted a series of detailed land surveys along the portions of the highway undermined between 2003 and 2008 to characterize the subsidence basins formed by longwall mining. PennDOT information has also been analyzed by another research group within the University (Gutiérrez, J.J., et al. 2010).

IV.C – Previous Experience with Undermining Pennsylvania's Interstate Highways

Prior to the 3rd assessment period, longwall mining under interstate highways within Greene and Washington Counties occurred in three separate episodes. Two of the three episodes occurred under Interstate 70 (I70) at Mine Eight-Four and one under Interstate 79 (I79) at the Gateway Mine (Figure IV-1).

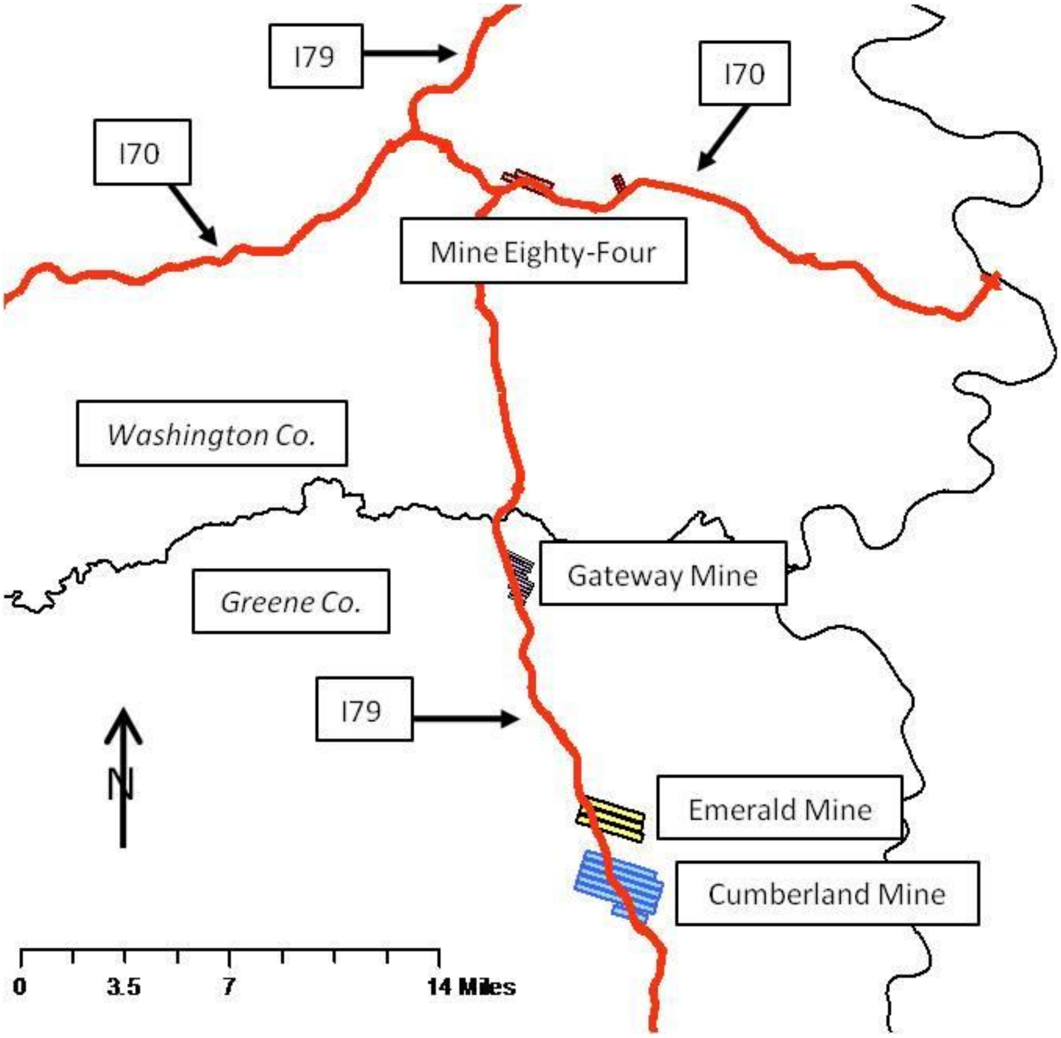

Figure IV-1 - Longwall panels that have undermined Pennsylvania Interstates.

IV.C.1 - I79, Gateway Mine

From June 1982 to September 1989, the Gateway Mine extracted coal from eight panels starting just north of the Ruff Creek Interchange, Exit 19 on I79, Greene County, PA (Figure IV-2). Panels were extracted in sequence progressing from south to north beneath the interstate. The panels were orientated with their long axis at an oblique angle to the interstate and averaged 511-ft wide and 4,100-ft long (Table IV-1). Longwall panels in the 1980's were much smaller than those observed in the 3rd assessment period. An average of 47 acres of surface land overlaid each of these panels with production rates of 5.1 days to mine one acre of longwall coal.

Table IV-1 - Gateway Mine longwall panel characteristics pertinent to the undermining of I79, 1982 to 1989 (Yancich, 1986).

Panel ID	Days to Mine	Acres	Dates Mined		Overburden, ft		Panel Dimensions		Avg. Over-burden, ft	Days to Mine 1 Acre	Width-to-Height
			Start	Finish	Min.	Max.	Width, ft	Length, ft			
0-Butt	336	38	6/16/82	5/18/83	675	850	522	3,218	763	8.8	0.68
1-Butt	235	37	6/18/83	2/8/84	675	950	567	2,842	813	6.4	0.7
2-Butt	258	45	9/15/84	5/31/85	660	910	504	3,957	785	5.7	0.64
3-Butt	344	45	9/13/85	8/23/86	655	905	534	3,969	780	7.6	0.68
4-Butt	179	46	9/15/86	3/13/87	665	930	503	3,967	798	3.9	0.63
7-Butt	158	51	2/15/88	7/22/88	690	890	499	4,468	790	3.1	0.63
8-Butt	170	56	8/15/88	2/1/89	740	915	489	4,995	828	3.0	0.59
9-Butt	227	58	2/15/89	9/30/89	765	890	470	5,386	828	4.0	0.57
Avg.	238	47					511	4,100	795	5.1	0.64

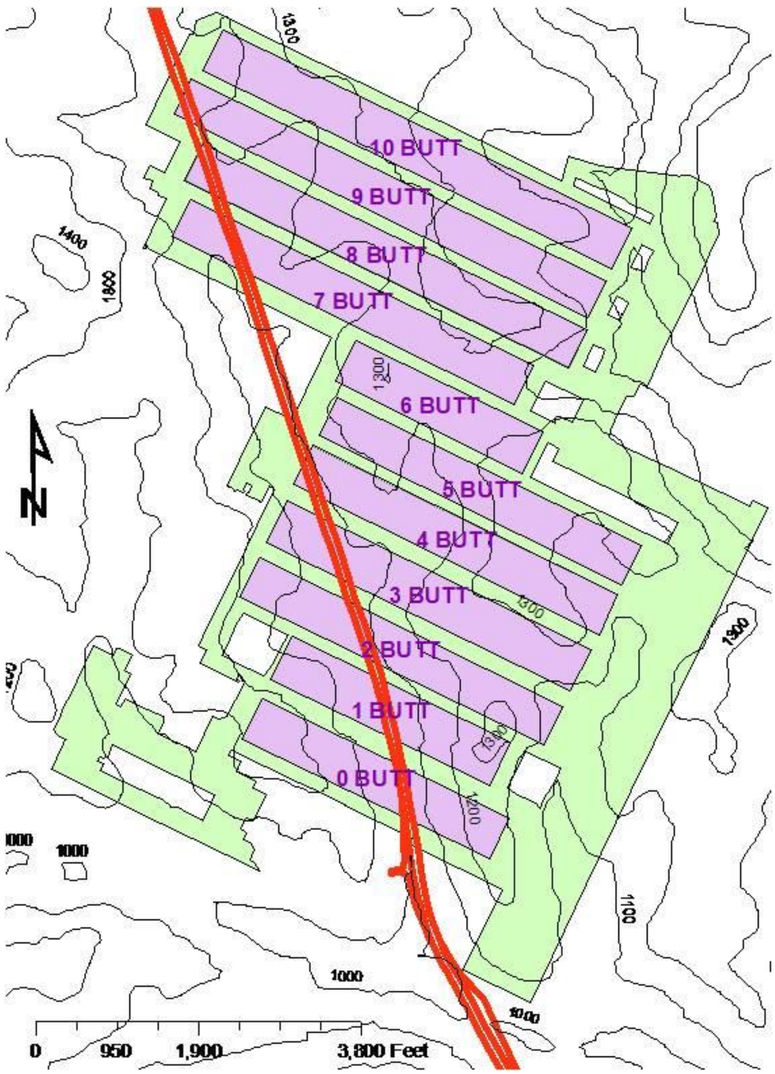

Figure IV-2 - Portions of I79 undermined by Gateway Mine longwall panels with topographic surface contours.

A Master's Thesis by Yancich at West Virginia University (1986) provides an excellent assessment of subsidence characteristics over three Gateway panels. This study included periodic surveys of fixed monuments along I79 and several houses during panel extraction. Transverse survey distances over the 511-ft wide Gateway panels were approximately 650-ft due to the oblique angle at which the panel intersected the highway. Monuments were placed along both the northbound and southbound lanes starting from the southern end of the Ruff Creek Interchange and extended 4,000-ft at 50-ft intervals. The lanes were separated by a grassy median strip approximately 60-ft wide. The final subsidence profiles, taken after the extraction of Panels 0-Butt, 1-Butt, and 2-Butt, are shown in Figure IV-3. The direction of mining relative to I79 is at angles of approximately 54-deg (0-Butt), 49-deg (1-Butt) and 47-deg (2-Butt).

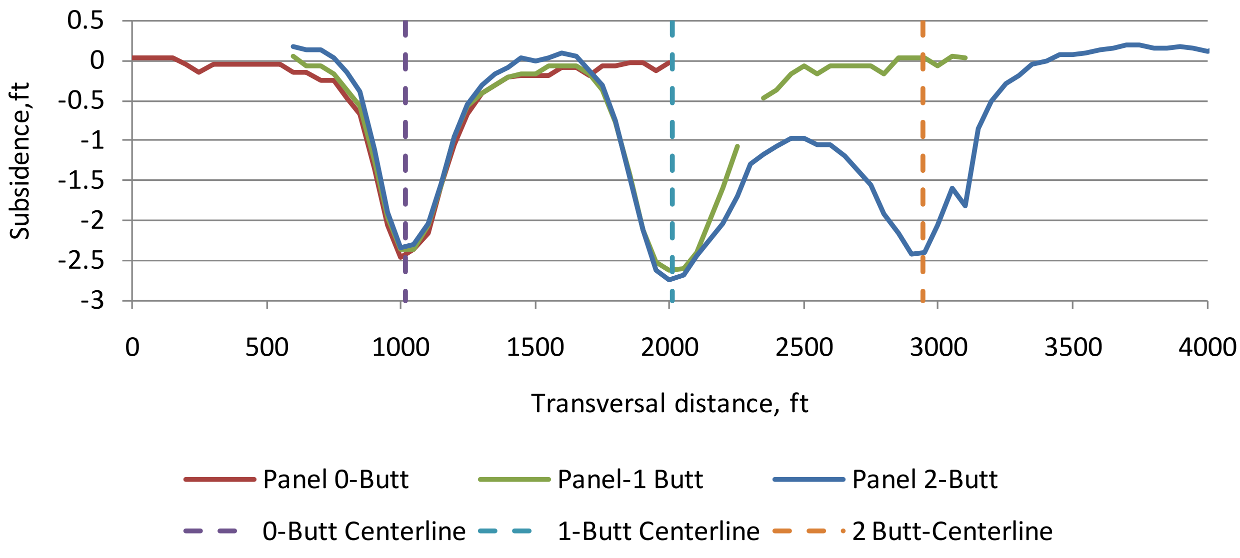

Figure IV-3 - Final subsidence profiles for three Gateway panels extracted under the northbound lanes of I79 (adapted from Yancich, 1986).

The surveys clearly showed the location of the three subsidence basins. The lack of a flat central subsidence profile confirmed that these panels were subcritical in character. The maximum subsidence values in the center of the subsidence basin were a fraction of the maximum possible subsidence for an extraction height of 6.5-ft. The ratio of the maximum subsidence to the mining height yielded subsidence factors (a) of 0.38 for 0-Butt, 0.42 for 1-Butt, and 0.37 for 2-Butt panels.

The surface slope and curvature were other means used to evaluate the impact of subsidence (Figure IV-4). The surface slope and curvature for the Gateway panels were derived from the previously discussed final subsidence profile (Figure IV-3). The maximum slope ranged between +1.9-pct to -1.56-pct, and the points of zero slopes were located at the centerlines of the longwall panels and gateroad entries (Figure IV-4a). The maximum curvature ranged between $+2x10^{-4}$/ft to $-2x10^{-4}$/ft and the areas of highest curvature occurred between the edges and centerlines of the panels (Figure IV-4b). Impacts to I79 were expected in areas of highest surface slope and curvature.

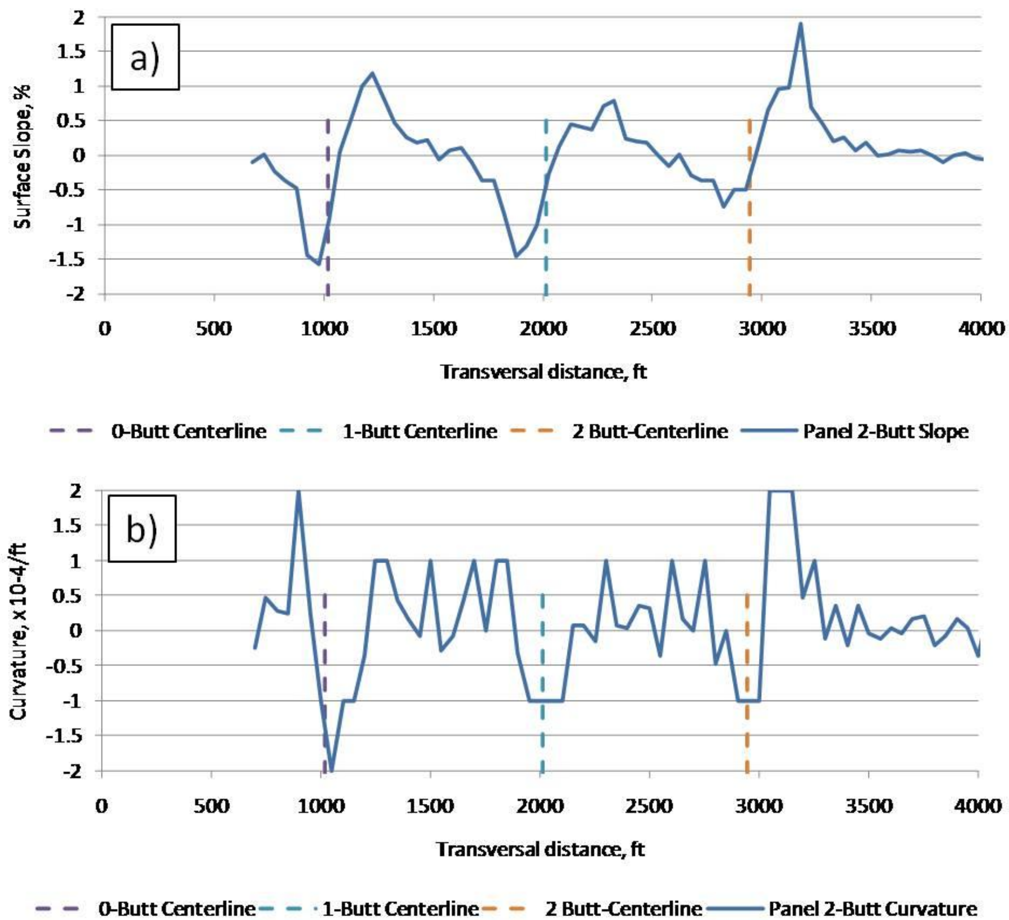

Figure IV-4 – Profiles of a) surface slope and b) curvature from three Gateway panels extracted under the northbound lanes of I79 (adapted from Yancich, 1986).

Yancich (1986) reported that only minor damage occurred to the northbound lanes of I79 that were undermined by longwall mining. Figure IV-5 shows repaired damage to I79 at: a) 900-ft along the survey profile, between the centerline and southern edge of the 0-Butt panel; b) 1,800-ft along the survey profile, near the southern edge of 1-Butt panel; and c) 3,300-ft along the survey profile, near the northern edge of 2-Butt panel. The Yancich study described a subset of impacts, making it difficult to determine the overall magnitude of damage and repairs associated with the development of multiple Gateway Mine subsidence basins under I79.

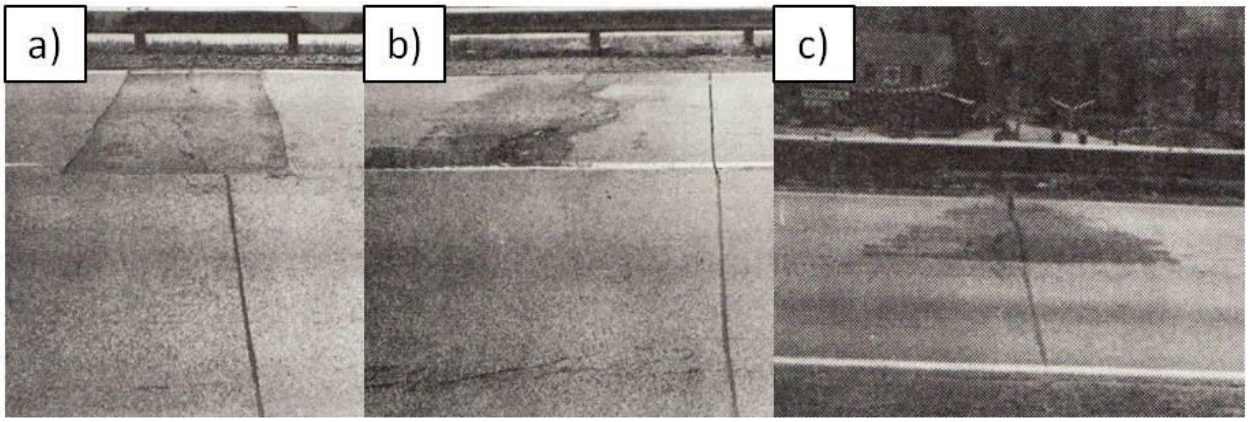

Figure IV-5 - Photographs of impacts to the northbound lanes of I79 over the 0-Butt (a), 1-Butt (b), and 2-Butt (c) panels of the Gateway Mine (Photographs from Yancich, 1986).

IV.C.2 - I70, Mine Eighty-Four

I70 is a major east-west highway that crosses the Pittsburgh Coalbed Basin in Washington County, PA. This interstate was first undermined by longwall panels from Mine Eighty-Four in 1987 and 1988. The southern extreme ends of two longwall panels (4B and 4C) intersected I70 (Figure IV-6). The authors were not able to find information on impacts of this initial episode of mining under I70.

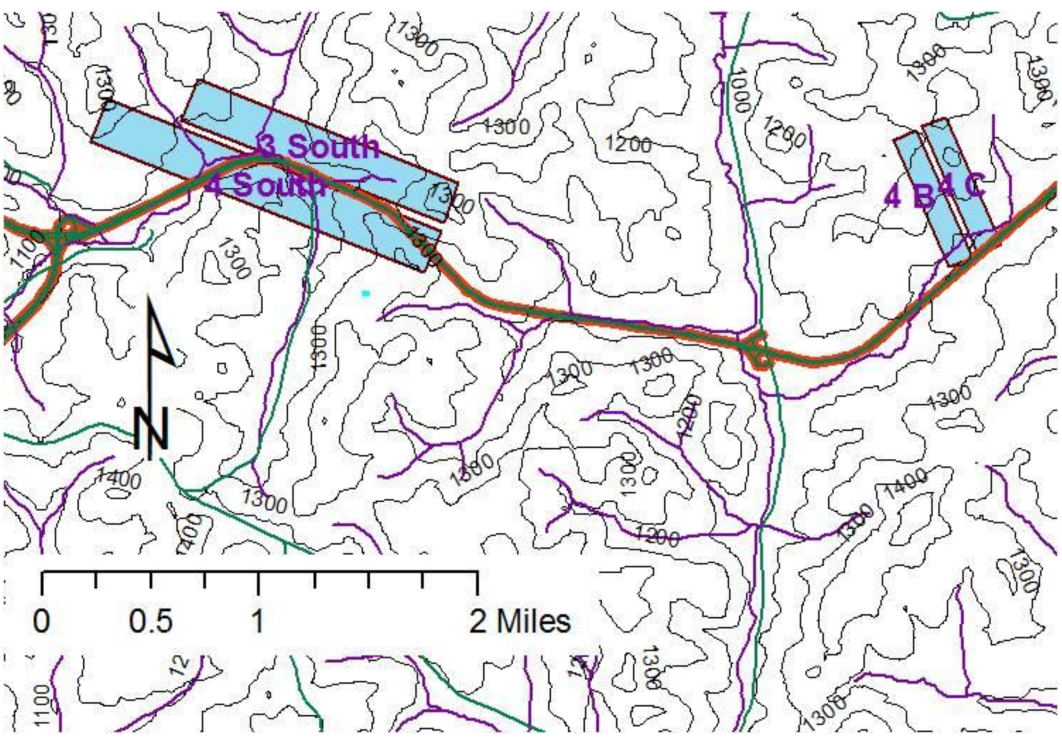

Figure IV-6 - Mine Eighty-Four longwall panels under I70.

A second undermining of I70 occurred from Nov. 22, 1999 to Oct., 16, 2000, when two longwall panels in South Strabane Township, Washington County, between the I79 interchange and State

Route 519, were mined (Figure IV-6). The surface topography over Mine Eighty-Four is gently rolling. Each panel averaged 1,059-ft wide, 6,810 to 8,685-ft long, and approximately 7-ft high. The layout of these panels was designed in an attempt to minimize impacts to the overlying interstate highway. As was noted from the survey information over the Gateway Mine, critical subsidence properties, such as surface slope and curvature, are less over the gateroad entries adjacent to longwall panels. The gateroad entries between 3- and 4-South Panels were designed to follow a ¾-mile section of I70, with the intent of minimizing damage to the highway. In theory the impacts along this section would be similar in nature since the vertical subsidence, slope, curvature and horizontal strains would not significantly change. Conversely the nature of impacts along highway sections that transect the 4-South Panel in its central and eastern ends should experience considerable variation.

Information on the undermining of this section of I70 was reported by O'Connor in 2001. An array of tiltmeters was installed adjacent to the highway to detect hazardous deformations to the highway during undermining. The 32 tiltmeters were outfitted with real-time data acquisition systems, capable of sounding an alarm if levels of tilt exceeded 0.002-ft/ft. During undermining PennDOT implemented a plan that: 1) temporarily supported the Zediker Station Road overpass (Figure IV-7), 2) dismantled some of some overhead signs, 3) imposed a speed-limit of 40-mph, 4) provided for lane closures and detours, and 5) visually monitored highway conditions (O'Connor, 2001). As a result, there were no accidents attributed to undermining this section of I70.

Figure IV-7 – Mitigation techniques used at the Zediker Station Road Overpass (Photograph from PA DEP files).

Table IV-2 - Mine Eighty-Four longwall panel characteristics pertinent to the undermining of I70, 1999 to 2000.

Panel ID	Days to Mine	Acres	Dates Mined		Overburden, ft		Panel Dimensions, ft		Avg. Over-burden ft	Days to Mine 1 Acre	Width-to-Height
			Start	Com-pleted	Min.	Max.	Width	Length			
3-South	101	165.8	11/22/99	3/2/00	520	765	1,057	6,810	643	0.61	1.65
4-South	221	215.2	3/9/00	10/16/00	550	760	1,061	8,685	655	1.03	1.62
Avg.	161	190.5					1,059	7,748	649	0.82	1.63

According to O'Connor (2001) vertical subsidence was measured and differed from prediction –

> "…..The ground surface ultimately deformed into a trough with maximum subsidence of three to five feet with surface tilting occurring around the margins of the trough. Precursor movement occurred ahead of the mine face, and outside the edges of the panel being mined. Predicted subsidence profiles, however, differed from the actual measured subsidence. As a consequence of differential tilt, (the) ground surface, pavement and structures were subjected to greater curvature and larger curvature strain than anticipated. Buried culverts and an overpass along the undermined section of I70 were not damaged, but longitudinal cracks developed between lanes, as did transverse bumps. This led to temporary lane closures as cracks were filled and bumps milled down. Along secondary roads, some transverse cracking occurred and the wall blocks in a railroad bridge abutment cracked and shifted…."

IV. D – Characteristics of Longwall Panels Undermining Portions of I79 during the 3rd Assessment Period

The location of the nine longwall panels, operated by Alpha Resources' Emerald and Cumberland Mines, and their associated overburdens are shown in Figure IV-8. As with the Gateway Mine panels, the Alpha longwall panels cut across I79 at oblique angles ranging between 45 to 80-deg. The overburden from the Pittsburgh Coalbed to the overlying I79 ranged between greater than 500-ft to less than 1,000-ft.

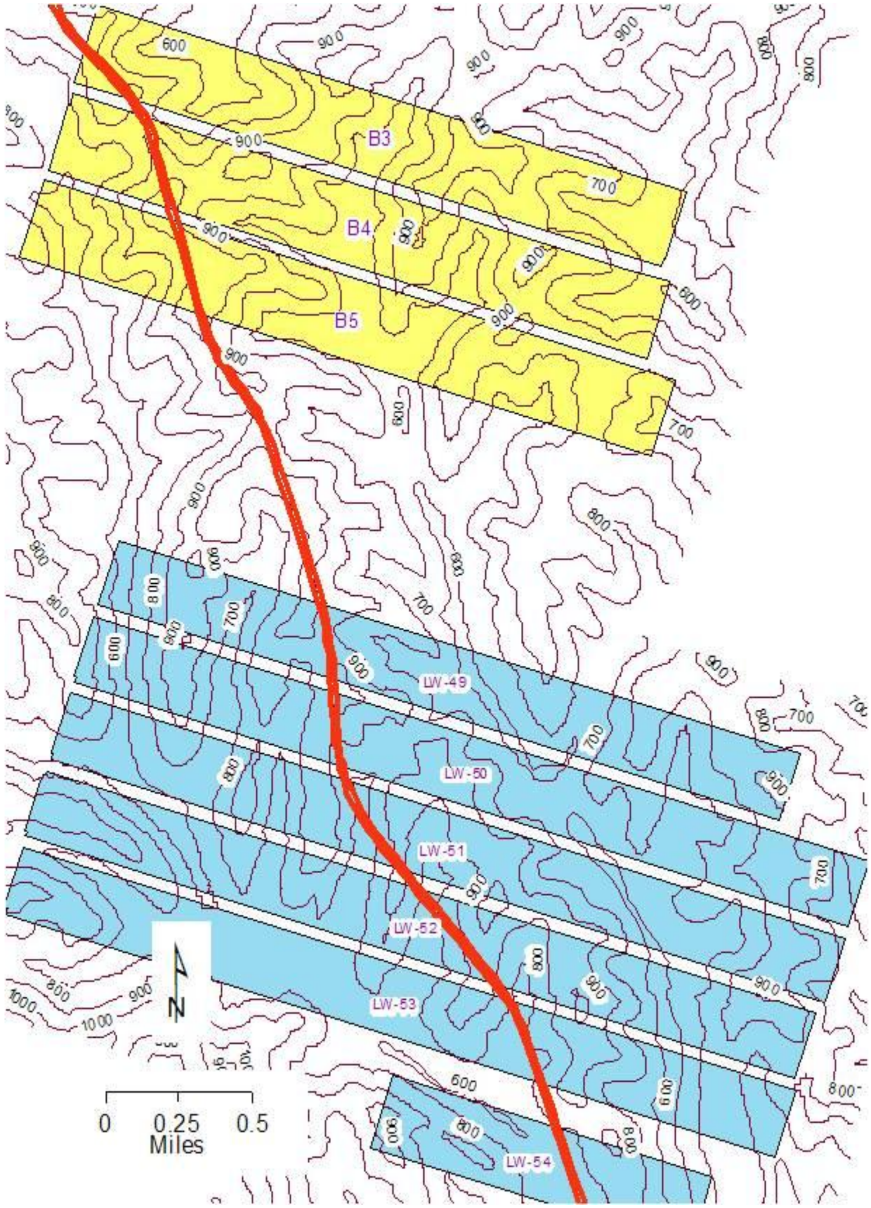

Figure IV-8 - Portions of I79 undermined by Emerald and Cumberland longwall panels including the overburden above the Pittsburgh Coalbed.

IV.D.1 - Panel Characteristics

The difference between the size and mining rate for the panels mined at the Gateway Mine in the 1980's and Emerald and Cumberland Mines during the 3rd assessment period was significant. The Emerald and Cumberland panels had an average width of 1,295-ft, an average length of 13,208-ft, and an average area of 372 acres (Table IV-3). This made these panels nearly 8 times larger in area than the Gateway panels. Another dramatic different was the rate of mining. The average Emerald and Cumberland panel was mined in 275 days, meaning that it took just 0.7 days to mine one acre (Table IV-3). This indicates that during an average day, the Emerald and Cumberland Mines mined approximately 7.6 times more coal than comparable longwall mines in the early 1980's. This is an important trend to note for this study since it indicated that the rate of mining has increased with time, which has, in turn, decreased the total length of time needed for the longwall subsidence basin to form and reach equilibrium.

Table IV-3 - Emerald and Cumberland longwall panel characteristics undermining I79 during the 3rd assessment period.

Panel ID	Days to Mine	Acres	Dates Mined		Panel Overburden, ft		Panel Dimensions, ft		Days to Mine an Acre
			Start	Completed	Min.	Max.	Width	Length	
B3	252	365	6/30/05	3/9/06	528	960	1,432	11,114	0.7
B4	274	370	3/20/06	12/19/06	601	955	1,430	11,289	0.7
B5	328	392	12/31/06	11/24/07	570	1,000	1,432	11,924	0.8
49	354	366	12/29/03	12/17/04	585	925	1,234	12,855	1.0
50	290	418	1/6/05	10/23/05	578	916	1,243	14,664	0.7
51	284	418	11/5/05	8/16/06	569	916	1,153	14,641	0.7
52	281	415	8/31/06	6/8/07	587	918	1,242	14,538	0.7
53	271	416	6/30/07	3/27/08	578	960	1,137	14,635	0.7
54*	144	189	4/9/08	As of 8/31/08	581	932	1,354	6,077	0.8
Avg	275	372					1,295	13,208**	0.76

* - for Panel 54, mining continued after 8/31/08
** - excluding Panel 54

IV.D.2 - Subsidence Properties

An evaluation of the subsidence properties of longwall panels operating under I79 demonstrate how this highway was impacted by the formation of the subsidence basin. Figure IV-9 illustrates some of the properties involved in defining a subsidence basin.

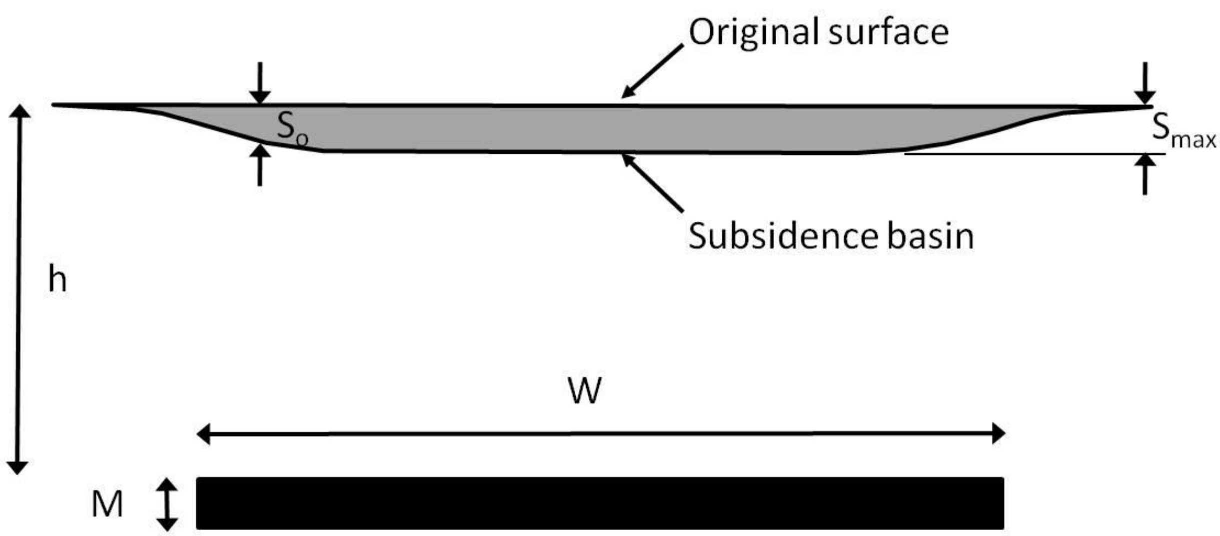

Figure IV-9 – Subsidence properties: M = coalbed thickness, W = longwall panel width, H = depth of cover, S = incremental value of vertical surface subsidence across the basin, and S_{max} = maximum vertical surface subsidence per panel.

As a general rule, the critical width (Lc) of a longwall panel is defined by:

Lc = W/H

When a critical width (Lc) is achieved, the maximum subsidence (S_{max}) potential is realized. If the critical width (Lc>1) is exceeded, the panel is said to have supercritical characteristics. In these cases, vertical subsidence reaches a maximum value, where S/S_{max} equals 1, and maintains that value over the center portion of the panel. For most US coalfields, the Lc is between 1.2 and 1.4 (Peng, 1992). In the case of the Emerald and Cumberland panels undermining I79, the W/H ratio averaged 1.7 (Table IV-4), producing a large, flat bottom subsidence basin. In contrast, the Gateway panels are subcritical in width with a W/H ratio that averaged 0.64. These subcritical panels never achieved their maximum subsidence potential and did not develop a flat bottom subsidence basin. The Mine Eight-Four panels were much like the Emerald and Cumberland panels. They were supercritical in width with a W/H ratio that averaged 1.63.

Table IV-4 - Subsidence properties of longwall panels that undermined I79 during the 3rd assessment period.

Mine	Panel ID	Mining height (M), ft	Max. subsidence (S_{max}), ft	Subsidence factor, (a)	Avg. 0verburden, ft (H)	Width-to-Height (W/H)
Emerald	B3	6.6	4.7	0.71	744	1.9
Emerald	B4	6.3	3.9	0.62	778	1.8
Emerald	B5	NA*	NA	NA	785	1.8
Cumberland	LW-49	7.4	4.6	0.62	755	1.6
Cumberland	LW-50	7.4	4.6	0.62	747	1.7
Cumberland	LW-51	7.4	4.7	0.64	743	1.6
Cumberland	LW-52	7.4	4.9	0.66	753	1.7
Cumberland	LW-53	7.7	5.3	0.69	769	1.5
Cumberland	LW-54	7.7	5.5	0.71	757	1.8
Avg.		7.2	4.8	0.66	759	1.7

* - NA = Not available

The vertical subsidence along I79 was monitored by the Emerald and Cumberland Mines and reported to PennDOT. Subsidence measurements were provided to the University as part of a PennDOT contract and were reported by Gutiérrez, J.J. et al. (2010). A profile of the vertical transversal subsidence for Cumberland Panel LW-49 is shown in Figure IV-10. The profile of a subsidence basin with a supercritical character was clearly developed. Zero and 1,234-ft transversal distances represented the boundaries between the gate road entries and the panel. Very small amounts of vertical subsidence occurred over the gate roads (S_o < 0.5-ft). At both margins of the panel, the vertical subsidence rapidly dropped off into a flat central basin. The maximum vertical subsidence (S_{max}) in the center of panel LW-49 reached 4.8-ft.

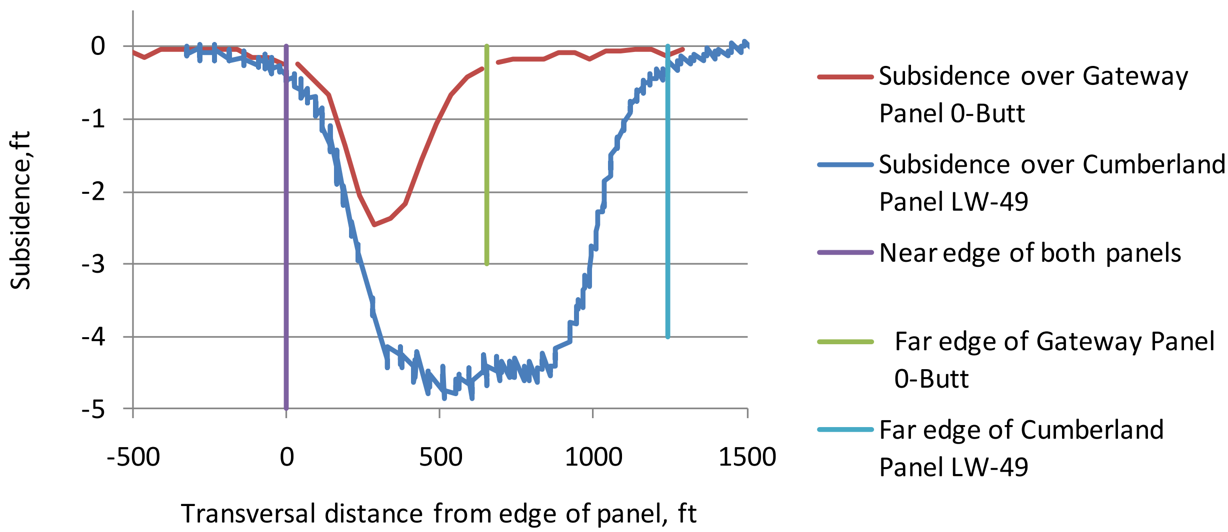

Figure IV-10 – Vertical transversal subsidence across Cumberland Panel LW-49 and comparison with vertical subsidence across Gateway Panel 0-Butt. Note the maintenance of a flat maximum vertical subsidence profile along the center of the subsidence basin indicative of supercritical subsidence basin. Also note the comparison with the vertical transversal subsidence across Gateway Panel 0-Butt which exemplifies a subcritical subsidence basin.

Figure IV-10 also provides a comparison between the supercritical Cumberland Panel 49 and the subcritical Gateway Panel 0-Butt. The Gateway subsidence basin also showed small amounts of vertical movement over the gate roads (S_o < 0.3-ft). The vertical subsidence rapidly dropped to a point and rose up to the other panel edge. The maximum vertical subsidence (S_{max}) in the center of this basin reached 2.5-ft.

Another important property is the subsidence factor (a). This property is calculated using the following relationship:

$a = S_{max} / M$

The average Emerald and Cumberland Mine subsidence factor for the panels undermining I79 was 0.66 (Table IV-4). The maximum subsidence factor was influenced by the geometry of the panel and geology of the overburden.

Zacharias and Karmis (2008) provide a means to estimate the percent of hard rock contained within an overburden when the maximum subsidence factor (a) and the W/h are known. As the percent of hard rock in the overburden increases, the maximum vertical subsidence decreases. The converse is also true. Hard rocks are typically sandstone and limestone, while soft rocks are shale, siltstone, clay stone, and coal. Using the procedure defined in Zacharias and Karmis (2008), the percent of hard rock at the Emerald and Cumberland panels was calculated to be 24-pct. All of the above properties are important in modeling the subsidence basin and account for the diverse range of subsidence conditions found in Pennsylvania's longwall mines.

IV.D.3 – Nature of Impacts

As the surface is undermined by a longwall panel, two distinct regions of deformation occur. First, as the longwall approaches, vertical subsidence begins slowly, speeds up until the inflection point in the subsidence event is encountered, and then begins to slow down until equilibrium is achieved (Figure IV-11). The inflection point moves forward with the advancing longwall face and generally represents the point where the vertical subsidence (S) is ½ S_{max}. The onset of vertical subsidence is defined by the angle of dynamic subsidence (δ_d) and the depth of cover (H). As the δ_d and H increase, the on-set of vertical subsidence increases. The inflection point defines the point of zero curvature. Ground surfaces in front of the inflection point are subjected to tension while surfaces behind the inflection point experience compression.

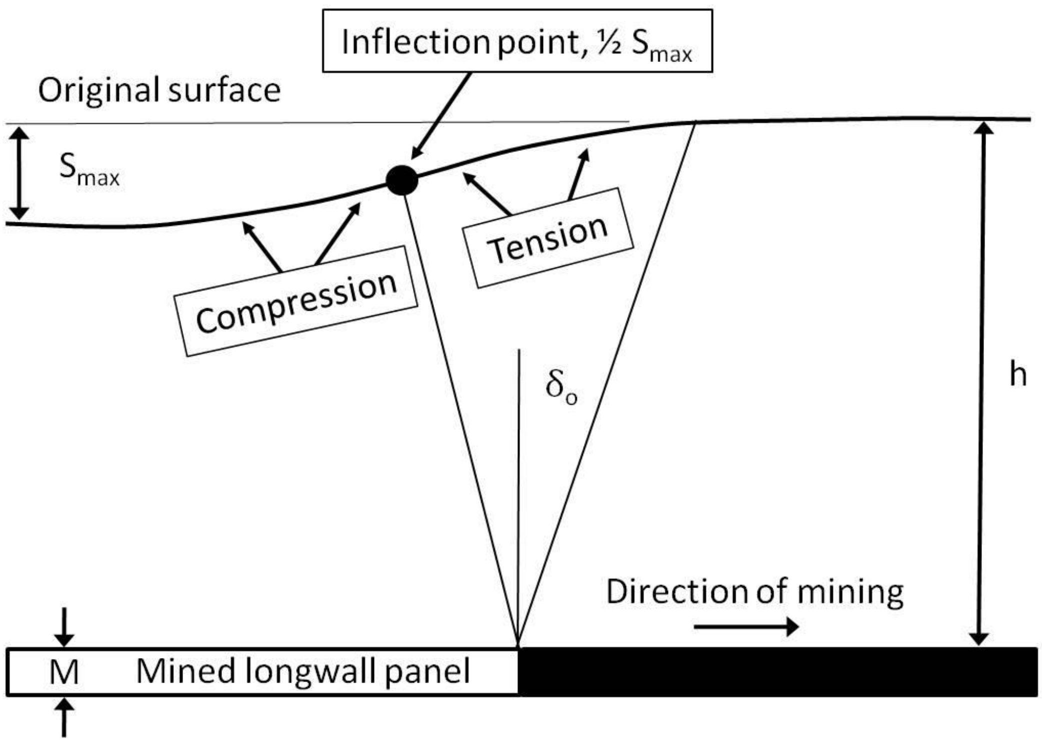

Figure IV-11 – Generalized relationship between vertical subsidence (S), h, δ_d, M and the occurrence of deformations caused by compression and tension.

These two general regions impacted the surface of I79 as the longwall panel moved under the highway. The methods developed by the Federal Highway Administration (Miller and Bellinger, 2003) helped to categorize the distress condition of jointed cement concrete-surface pavements. Four general categories with 16 subcategories of distress were defined (Table IV-5). These methods were applied to I79 in Greene County where the concrete sections were 62.5-ft long and were covered by several inches of asphalt (Painter, 2010).

TableIV-5 - Jointed concrete surface pavement distress types (Miller and Bellinger, 2003).

Category	**#**	**Distress Type**
Cracking	1	Corner Breaks – A portion of the slab separated by a crack, which intersects the adjacent transverse and longitudinal joints, describing approximately a 45-deg angle with the direction of traffic. The length of the sides is from 1-ft to one-half the width of the slab on each side of the corner.
	2	Durability Cracking – Closely spaced, crescent-shaped hairline cracking pattern, occurring adjacent to joints, cracks, or free edges. Initiates in slab corners with dark coloring of the cracking pattern and surrounding area.
	3	Longitudinal Cracking – Cracks that are predominantly parallel to the pavement centerline.
	4	Transverse Cracking – Cracks that are predominantly perpendicular to the pavement centerline.
Joint Deficiencies	5	Joint Seal Damage – Conditions which enable incompressible materials or water to infiltrate the joint from the surface. Typical types of joint seal damage are: extrusion, hardening, adhesive failure (bonding), cohesive failure (splitting), or complete loss of sealant; intrusion of foreign material in the joint; and weed growth in the joint.
	6	Spalling of Longitudinal Joint – Cracking, breaking, chipping, or fraying of slab edges within 0.3 m from the face of the longitudinal joint.
	7	Spalling of Transverse Joint – Cracking, breaking, chipping, or fraying of slab edges within 0.3 m from the face of the transverse joint.
Surface Defects	8	Map Cracking and Scaling – Map cracking is a series of cracks that extend only into the upper surface of the slab. Larger cracks frequently are oriented in the longitudinal direction of the pavement and are interconnected by finer transverse or random cracks. Scaling is the deterioration of the upper concrete slab surface, normally 3 mm to 13 mm, and may occur anywhere over the pavement.
	9	Polished Aggregate - Surface mortar and texturing worn away to expose coarse aggregate.
	10	Popouts - Small pieces of pavement broken loose from the surface, normally ranging in diameter from 25 mm to 100 mm, and depth from 13 mm to 50 mm.
Miscellaneous Distress	11	Blowups - Localized upward movement of the pavement surface at transverse joints or cracks, often accompanied by shattering of the concrete in that area.
	12	Faulting of Transverse Joints and Cracks - Difference in elevation across a joint or crack.
	13	Lane-to-Shoulder Dropoff - Differences in elevation between the edge of slab and outside shoulder; typically occurs when the outside shoulder settles.
	14	Lane-to-Shoulder Separation - Widening of the joint between the edge of the slab and the shoulder.
	15	Patch/Patch Deterioration - A portion, greater than 0.1 m^2, or all of the original concrete slab that has been removed and replaced, or additional material applied to the pavement after original construction.
	16	Water Bleeding and Pumping - Seeping or ejection of water from beneath the pavement through cracks. In some cases, detectable by deposits of fine material left on the pavement surface, which were eroded (pumped) from the support layers and have stained the surface.

Several of the distress types described in Table IV-5 can be associated with surface deformations induced by longwall mining. For example, "blowups" (No. 11, Table IV-5), can be associated with compressive surface deformations. Accordingly, blowups would not be expected until after the longwall face and the inflection point have moved under a point on the surface. Therefore they should occur later in the formation of the subsidence basin. Some other concrete distress types, i.e. transverse cracking (No. 4, Table IV-5), spalling of transverse joint (No. 7, Table IV-5), faulting of transverse joints and cracks (No. 12, Table IV-5), are often associated with tensile surface deformations. These concrete distress types should be more frequent earlier in the subsidence basin formation, often in association with the longwall face moving under a point on the surface.

IV.E – Observations During Undermining of I79

PA DEP staff routinely visited I79 while the longwall face was mined under the highway. During these visits they often took pictures of highway conditions and, on occasion, made written observations. The visual clues and written descriptions were usually sufficient to establish the general location and perspective of the photographs. Documentation of the impacts to I79 in response to longwall mining during the 3rd assessment period follows.

IV.E.1 – Emerald Panels

Three Emerald panels impacted the overlying sections of I79 (Figure IV-12). The overburden at the area where I79 crossed these three panels ranged from approximately 700 to over 900-ft (Figure IV-12). I79 crossed all the Emerald panels at oblique angles ranging between 35 to 70-deg.

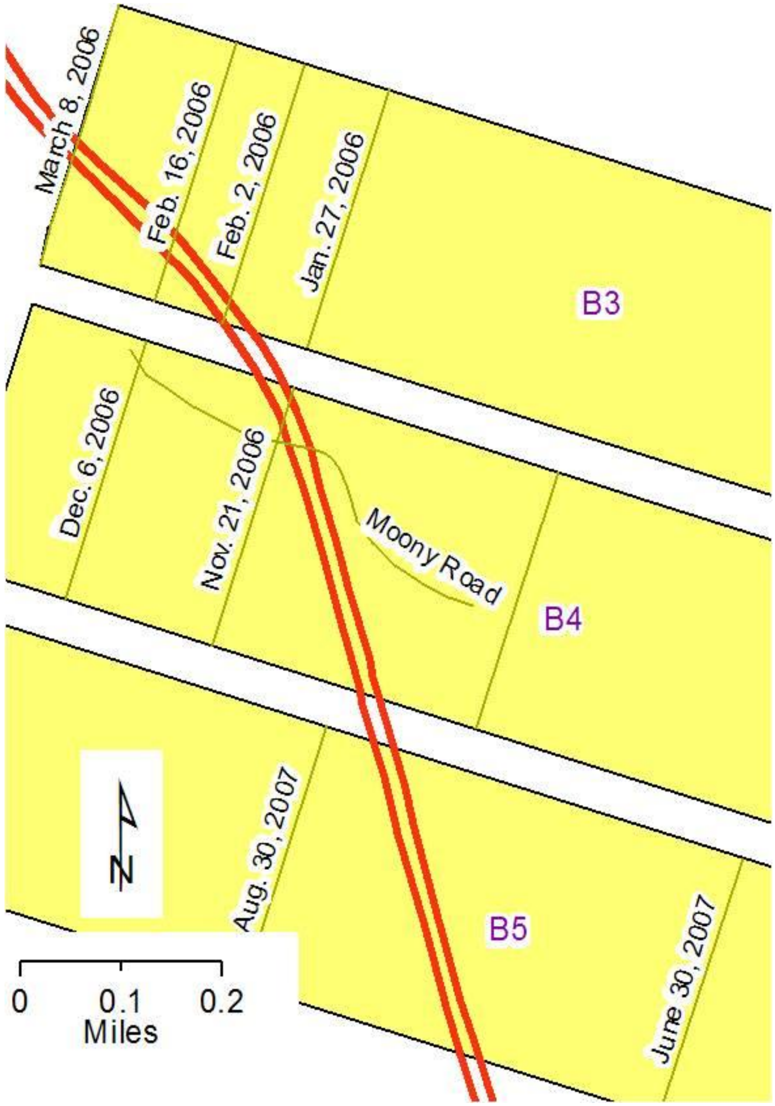

Figure IV-12- Locations of Emerald Panels B3, B4, and B5 with dated face positions during undermining of I79. Also shown is the section of Moony Road where it intersects I79.

IV.E.1.a - Panel B3

The Emerald Panel B-3 impacted the overlying sections of I79 from January 27, 2006 to February 28, 2006 (Figure IV-12). By January 27, 2006 the initial tensile subsidence wave from Panel B-3 began to impact I79. The impact at this point was predicted to be marginal. PennDOT workers removed signs and marked the road for monitoring purposes. The overburden at the I79 crossing of panel B-3 ranged from 750 to 850-ft (Figure IV-12). Results from undermining Panel B-3 were expected to be different from other panels mined during the 3rd assessment period because the highway bisected only the corner-end of the panel.

Cracks along the I79 were first observed on February 14, 2006, in the northbound lanes. One section of pavement contained longitudinal cracking (No. 3, Table IV-5) with a separation of about 1-in. Other longitudinal cracking was observed closer to the edges of the road with separations between 1/4 and 1/2-in. At this point most of I79 had experienced less than half of the total expected subsidence. The surface curvature produced at this time would have exerted almost exclusively tensile forces on the highway foundation. No compression or buckling road surfaces were observed at this time.

On February 21, 2006, the southbound lanes were still relatively free of impacts. A small transverse compression heave or blowup (No. 11, Table IV-5 developed in the northbound passing lane (Figure IV-13a) and required milling and patching (Figure IV-13c). In addition, a large lane-to-shoulder separation (No. 14, Table IV-5) formed along the boundary between the pavement and the shoulder (Figure IV-13b). Between February 22, 2006 and March 8, 2006, PennDOT restricted traffic to one-lane and did extensive patching to the shoulders of both the north and southbound sides (Figure IV-13d). While this area had not required extensive milling, some heaving was noted near the end of the panel. The surface curvature produced at this time would have exerted a dominant compressive force on the highway foundation. The lane-to-shoulder separation might have been caused by the heaving of large concrete slabs in response to this compressive loading.

Figure IV-13 – Panel B3 photographs showing (a) a transverse compression heave, (b) lane-to-shoulder separation ,(c) blowup compression bump being milled, (d) single lane restrictions with longitudinal patching, February 21, 2006 (Photographs from PA DEP files).

IV.E.1.b - Panel B4

Panel B4 was undermined between October 22, 2006 and December 6, 2006 (Figure IV-12). The overburden at the I79 crossing of Panel B-4 ranged from approximately 820 to 920-ft (Figure IV-12). On October 30, 2006, the longwall face was located directly underneath the southbound lane at the southern edge of panel B-4 and no new subsidence damage was observed to I79.

PennDOT personnel installed cameras to take photos of the roadway every 5-min. (Figure IV-14a). Some minor longitudinal and transverse cracking (No. 3 & 4, Table IV-5) were observed (Figure IV-14b and c). Many of these cracks existed prior to undermining and were observed to extend and widen during the observation period.

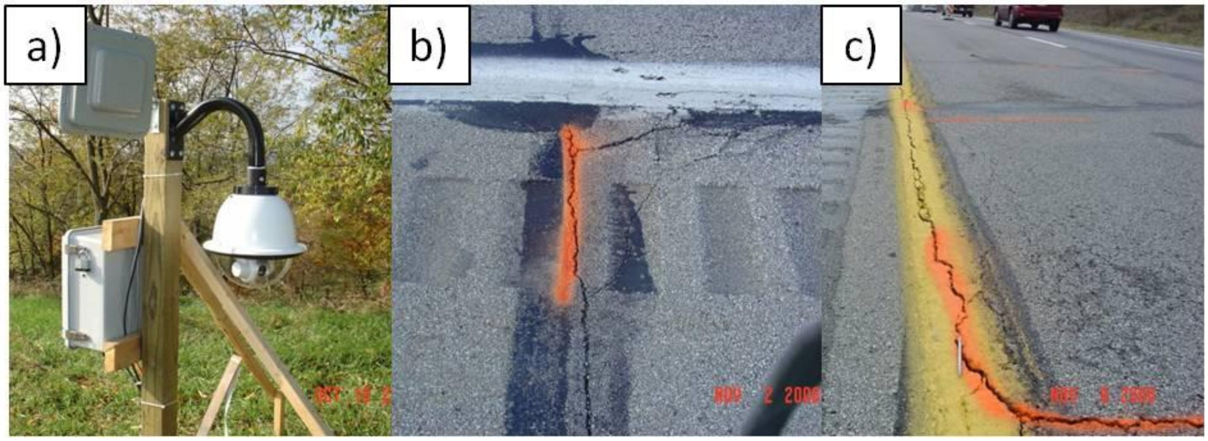

Figure IV-14 – Panel B4 Photograph showing a (a) remote camera system, (b) transverse crack, and (c) longitudinal crack (Photographs from PA DEP files).

On November 6, 2006, some hairline cracks were visible in the northbound lanes. Minor lane-to-shoulder separations (No. 14, Table IV-5) occurred in both northbound and southbound lanes by November 16, 2006 (Figure IV-15a). These separations were typically 1/8 to 3/4-in wide. Some minor lane-to-shoulder drop-off (No. 13, Table IV-5) was also observed in these same areas. On November 22, 2006, a large blowup (No. 11 Table IV-5 and Figure IV-15b) and deformed guard rails were observed (Figure IV-15c).

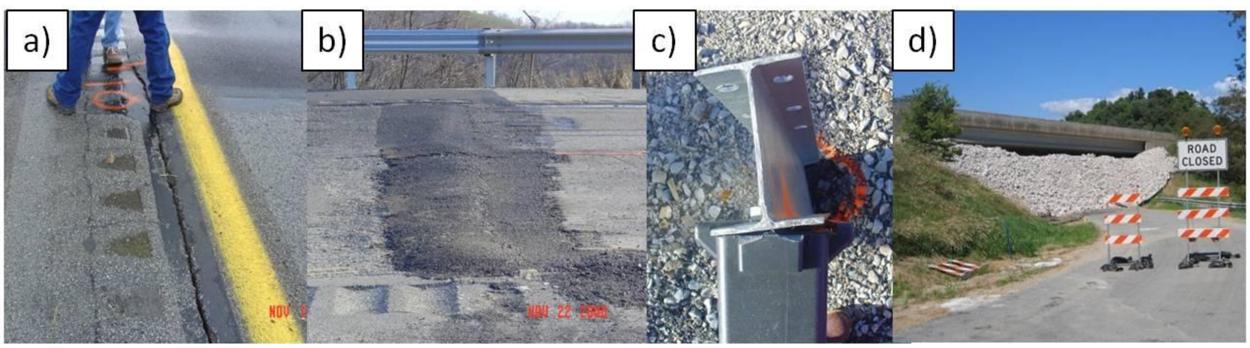

Figure IV-15 - Panel B4 photograph showing a (a) lane-to-shoulder separation, (b) blowup, (c) distressed guard rails, and (d) mitigation method to protect I79 Bridge at Moony Road (Photographs from PA DEP files).

Moony Road (also known as Tower Road) crosses under I79 in this area (Figure IV-12). PennDOT placed aggregate underneath both the north- and southbound overpass structures as well as in the median area (Figure 15d). Once the aggregate was at sub-grade, a temporary section of road was built in the median area. The southbound traffic was relocated to the median area and the southbound structure (bridge deck, beams, and parapets) were then removed. The structure was replaced with a two lane asphalt roadway. When the work was completed on the southbound side, the same measures were completed on the northbound overpass structures.

IV.E.1.c - Panel B5

Panel B5 was undermined from June 30, 2007 to September 30, 2007 (Figure IV-12). The overburden at the I79 crossing of panel B5 ranged between approximately 880 and 940-ft. No roads cross over or under this portion of I79, however, a communications tower was located near the highway and the impact to this structure is explained later in the report.

PennDOT utilized remote data acquisition systems and transferred information collected while I79 was undermined to their offices for review and analysis (Figure IV-16a). Monitoring occurred 24-hours a day and traffic was limited to one lane in each direction at a rate of 45-mph. Tensile forces caused the first recognized impacts. For example, on June 21, 2007, a corner break (No. 1, Table IV-5) was observed (Figure IV-16b). Later, in late July and early August (Figure IV-16c and d) spalling of transverse joints (No. 6, Table IV-5) and transverse cracking (No. 4, Table IV-5) occurred. Many of the joints and cracks ranged in size between 1/8 and 2-in.

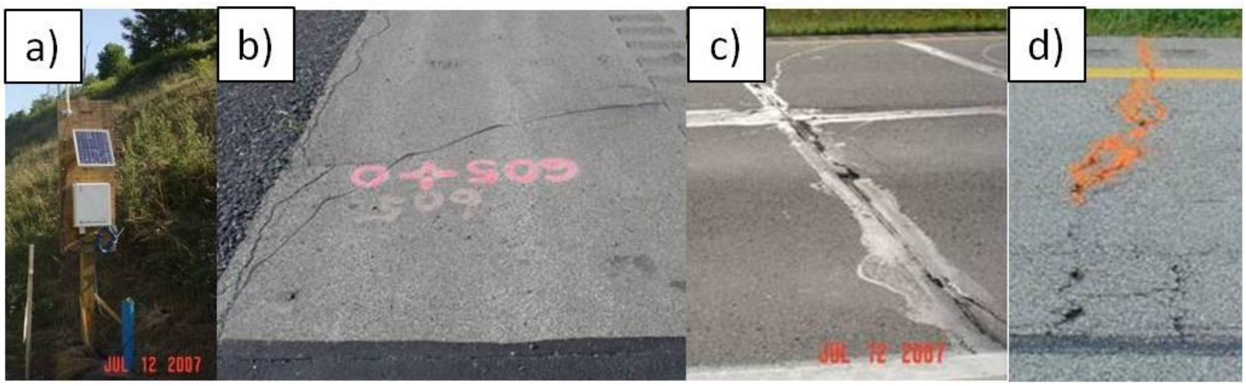

Figure IV-16 – Panel B5 photographs showing (a) data acquisition equipment, (b) corner breaks, (c) transverse joints, and (d) transverse cracks (Photographs from PA DEP files).

In August, the compressive failures became more dominant. Lane-to-shoulder dropoff (No. 13, Table IV-5) and separation (No. 14, Table IV-5 and Figure IV-17a) and blowup (No. 11, Table IV-5 and Figure IV-17b) were observed. In addition, transverse cracks (No. 4, Table IV-5) continued to occur (Figure IV-17c). Open joints were either filled or patched. The blowups were repaired by milling and patching. Figure IV-17d provides a view of the subsidence basin as of September 11, 2007.

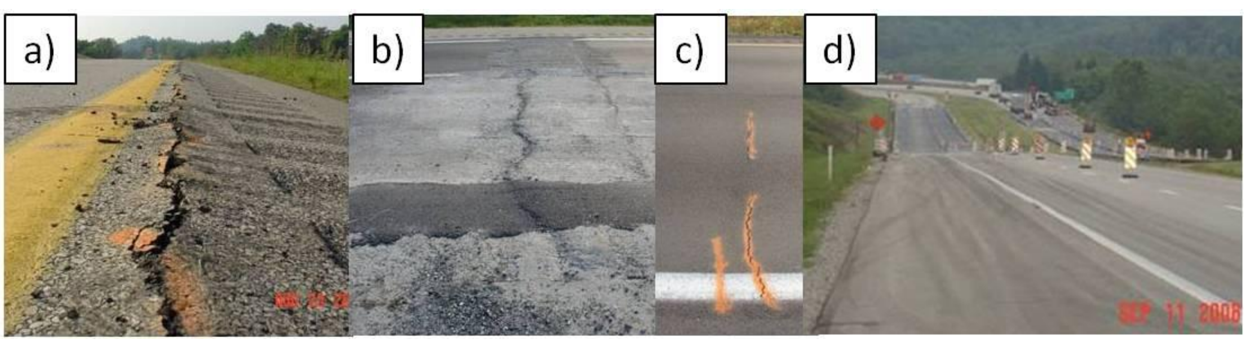

Figure IV-17 – Panel B5 photographs showing (a) lane-to-shoulder separation, (b) blowups, (c) transverse cracks, and (d) view of the final subsidence basin (Photograph from PA DEP files).

IV.E.2 – Cumberland, Panels

Six Cumberland panels impacted the overlying sections of I79 (Figure IV-18). No photographs were available for Panel LW-49 (September and October, 2004). The distance between Panels LW-53 and LW-54 was much larger than any other panel. The larger distance was related to the inclusion of a main entry system running between both longwall panels. The overburden at the area of I79 crossing these six panels ranged between approximately 760 to almost 1,000-ft (Figure IV-18). In all of these panels, I79 crossed the Cumberland panels at oblique angles ranging between 35 to 70-deg.

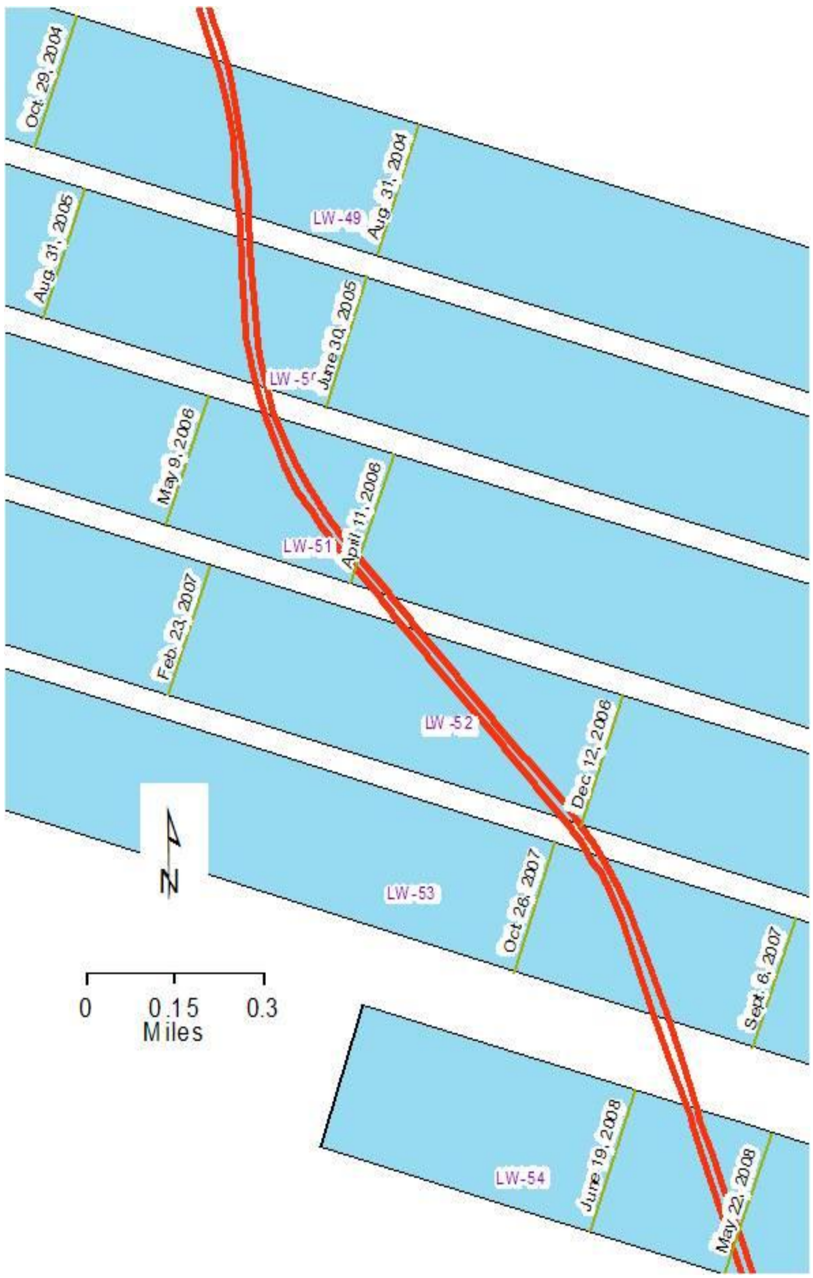

Figure IV-18 – Location of Cumberland Panels LW-49, LW-50, LW-51, LW-52, LW-53, and LW-54 with associated face positions while the undermining of I79 occurred.

IV.E.2.a - Panel LW-49

Panel LW-49 was mined from December 29, 2003 to December 17, 2004. The I79 portion of the panel was undermined during end of September and beginning of October 2004. The overburden at the I79 crossing of Panel LW-49 ranged between approximately 810 and 900-ft (Figure IV-18). No impacts or photographs relating to the undermining of this section were found.

IV.E.2.b - Panel LW-50

Panel LW-50 was mined from January 6, 2005 to October 23, 2005. The I79 portion of the panel was undermined during mid-July and early August 2005. The overburden at the I79 crossing of Panel LW-50 ranged between approximately 780 and 910-ft (Figure IV-18).

By August 3, 2005 the longwall panel had mined past I79 and PennDOT began patching damaged sections (Figure IV-19a). On that same day, a corner break (No. 1, Table IV-5) was observed (Figure IV-19b). Two days later, faulting occurred along a joint (No. 12, Figure IV-19c). Figure IV-19d shows the subsidence basin on August 11, 2005.

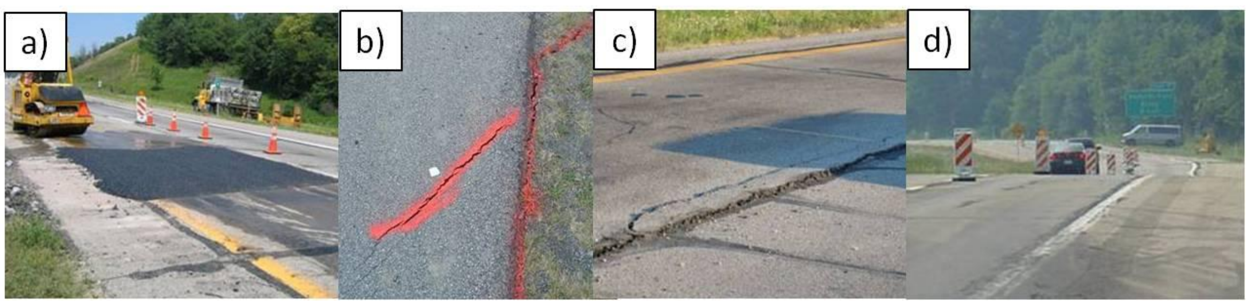

Figure IV-19 - Panel LW-50 photographs showing (a) patching activity, (b) a corner break, (c) faulting of joints, and (d) subsidence basin (Photographs from PA DEP files).

IV.E.2.c - Panel LW-51

Panel LW-51 was mined from November 5, 2005 to August 16, 2006 (Figure IV-18). The I79 portion of the panel was undermined during April and early May 2006. The overburden at the I79 crossing of Panel LW-51 ranged between approximately 650 and 820-ft (Figure IV-18).

Transverse joint spalling (No. 7, Table IV-5) was observed on April 21st (Figure IV-20a). On April 27, 2005 PennDOT patched separations (No. 14, Table IV-5) along the lane-to-shoulder area (Figure IV-20b). Figure IV-20c shows compression along highway guard rail and a photograph on May 11, 2005 (Figure IV-20d) shows a recently repaired blowup (No. 11, Table IV-5).

Figure IV-20 – Panel LW-51 photographs showing (a) spalling of transverse joint, (b) lane-to-shoulder separation, (c) compression of guard rail, and (d) blowup (Photographs from PA DEP files).

IV.E.2.d - Panel LW-52

Panel LW-52 was mined from August 31, 2006 to June 8, 2007 (Figure IV-18). The I79 portion was undermined during December 2006 and January 2007. The overburden at the I79 crossing of Panel LW-52 ranged between approximately 680 and 840-ft (Figure IV-18).

On December 21, 2006 the longwall panel began to advance underneath I79 at a 30-deg angle, and a large transverse crack (No. 7, Table IV-5) was observed (Figure IV-21a). Corner breaks (No. 1, Table IV-5) were observed on January 4, 2007 as the longwall face advanced to half the transversal distance (Figure IV-21b). PennDOT used saw cuts to de-stress the highway on January 11, 2007 (Figure IV-21c). Figure IV-21d shows the resurfaced highway on July 12, 2007 approximately 6-months after longwall mining.

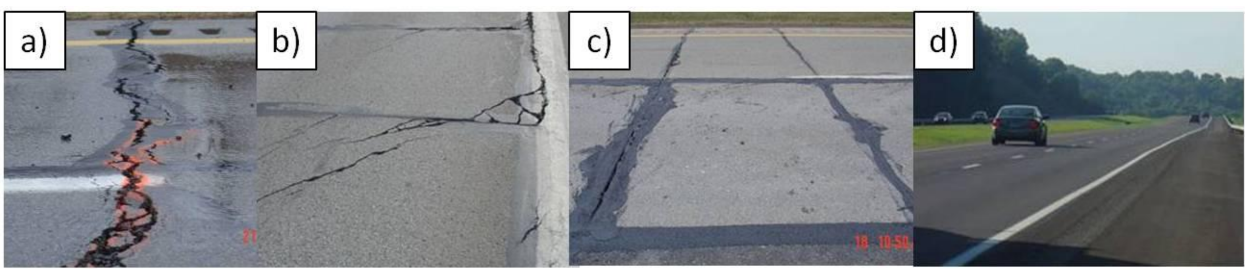

Figure IV-21 – Panel LW-52 photographs showing (a) transverse cracking, (b) corner breaks, (c) highway deformation between saw cuts in the slabs, and (d) rehabilitated highway surface (Photographs from PA DEP files).

IV.E.2.e - Panel LW-53

Panel LW-53 was mined from June 30, 2007 to March 27, 2008 (Figure IV-18). The I79 portion was mined during mid September and late October 2007. The overburden at the I79 crossing of Panel LW-53 ranged between approximately 670 and 730-ft (Figure IV-18).

Several months prior to the undermining of I79, PennDOT used saw cuts on sections of highway slabs to help mitigate future deformations (June 26, 2007, Figure IV-22a). Temporary patching occurred during various stages of I79 undermining (Sept. 27, 2007, Figure IV-22b). On Oct. 4, 2007, I79 was directly over the center portion of the advancing longwall face. Faulting of transverse joints (No. 12, Table IV-5) and lane-to-shoulder drop-off (No. 13, Table IV-5) were observed by PA DEP personnel.

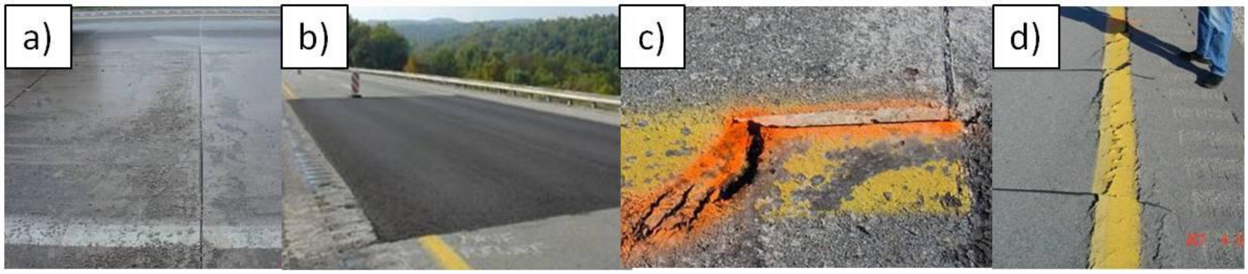

Figure IV-22 – Panel LW-53 photographs showing (a) pre-mining saw cuts, (b) temporary patching, (c) faulting of transverse joints, and (d) lane-to-shoulder drop-off (Photographs from PA DEP files).

IV.E.2.f - Panel LW-54

Panel LW-54 was mined from April 9, 2008 to August 31, 2008 (Figure IV-18). The I79 portion of the panel was undermined during mid May and mid June 2008. The overburden at the I79 crossing of Panel LW-54 ranged between approximately 640 and 700-ft (Figure IV-18).

During the mining of Panel LW-54, lane-to-shoulder drop-off (No. 13, Table IV-5) and transverse (No. 4, Table IV-5) and longitudinal cracking (No. 3, Table IV-5) occurred (Figures IV-23a and b). Figure IV-23c shows the final subsidence basin as of June 12, 2008.

Figure IV-23 – Panel LW-54 photographs showing a (a) lane-to-shoulder drop-off, (b) transverse and longitudinal cracking between saw cuts, and (c) final subsidence basin (Photographs from PA DEP files).

IV.F – Summary Points

Two Interstate highways in southwestern Pennsylvania have been undermined by 21 longwall panels since the early 1980s. Longwall panels in the 1980s were significantly narrower than contemporary longwall panels, and often produced subcritical subsidence characteristics. The nine recent longwall panels located under I79 (2003 to 2008) were among some of the widest in the US, producing supercritical subsidence characteristics. In addition, the rate of mining has steadily increased with time, which has in turn decreased the total length of time needed for the longwall subsidence basin to form and reach equilibrium.

In general, tension type distress features, i.e. longitudinal and transverse cracking, began to impact the highway prior to and during the undermining of the highway by the longwall face. Conversely, compression type distress features, i.e. blowups or heaving, were more common after the longwall face had passed underneath the highway.

In the cases studied, longwall mining resulted in numerous localized effects. Some of the effects were transitory in nature as the subsidence wave passed through the area. These effects were successfully managed through traffic controls and temporary support measures. In general, damage effects were addressed through routine road maintenance such as milling, patching, repaving, and straightening guardrails. An exception was the preemptive approach taken by PennDOT to prevent a potential catastrophic differential subsidence event of the bridges carrying I79 over Mooney (Tower) Road. The Commonwealth of Pennsylvania spent over 19 million dollars (Painter, 2010) monitoring and rehabilitating sections of I79 impacted by longwall mining (Table IV-6).

Table IV-6 – Cost to maintain, monitor, and repair I79 during undermining (Painter, 2010).

Year	Detour Preparation Cost, $	Monitor and Equipment, $	Construction, $	Total, $
2002-2003	6,263,597			6,263,597
2004		244,048	467,608	711,656
2005		65,309	1,644,856	1,710,165
2006		239,176	3,192,371	3,431,548
2007		152,871	3,090231	3,243,102
2008		230,131	4,016737	4,246,868
Total 2003 to 2008				19,606936

* - Estimated

Impacts to I79 could be considered significant in three ways. First, traffic through the monitoring areas was adversely affected for a span of over 5-years. During active mining or repair period, the speed-limit was reduced to 45-mph and the lanes were reduced from two to one in both directions. Second, longwall mining impacted the vertical curvature and sight distances of the highway. Third, the Commonwealth of Pennsylvania was required to spend approximately 20 million dollars monitoring and rehabilitating sections of I79 impacted by longwall mining.

However, traffic flow was safely maintained at all times. State Police reported no driving related injuries as a result of longwall mining. The majority of the damages noted consisted of longitudinal cracking, mainly along the edges of the highway, and heaving, mainly along transverse joints. These kinds of damages are within the range of commonly observed distress concrete documented by the Federal Highway Administration (FHA) (Table IV-5). The vast majority of highway deformations were transient; therefore the highway monitoring and rehabilitation efforts were concentrated over a span of several months for each panel mined.

One fact is certain, in the cases that have transpired to date, it has been more cost effective to allow longwall mining to proceed than to condemn the coal needed to provide support for the highway. The cost to condemn the coal was estimated by O'Connor (2001) at approximately one order of magnitude higher than the current repair cost sighted earlier.